3.1 ATTENUATION

Attenuation of a light signal as it propagates along a fiber is an important consideration in the design of an optical communication system, since it plays a major role in determining the maximum transmission distance between a transmitter and a receiver or an in-line amplifier. The basic attenuation mechanisms in a fiber are absorption, scattering, and radiative losses of the optical energy.[1-5] Absorption is related to the fiber material, whereas scattering is associated both with the fiber material and with structural imperfections in the optical waveguide. Attenuation owing to radiative effects originates from perturbations (both microscopic and macroscopic) of the fiber geometry.

In this section we shall first discuss the units in which fiber losses are measured and then present the physical phenomena giving rise to attenuation.

3.1.1 Attenuation Units

As light travels along a fiber, its power decreases exponentially with distance. If $P(0)$ is the optical power in a fiber at the origin (at $z = 0$), then the power $P(z)$ at a distance z further down the fiber is

$$P(z) = P(0)e^{-\alpha_p z} \tag{3-1a}$$

where

$$\alpha_p = \frac{1}{z}\ln\left[\frac{P(0)}{P(z)}\right] \tag{3-1b}$$

is the fiber *attenuation coefficient* given in units of, for example, km^{-1}. Note that the units for $2z\alpha_p$ can also be designated by *nepers* (see App. D).

For simplicity in calculating optical signal attenuation in a fiber, the common procedure is to express the attenuation coefficient in units of *decibels per kilometer*, denoted by dB/km. Designating this parameter by α, we have

$$\alpha\,(\text{dB/km}) = \frac{10}{z}\log\left[\frac{P(0)}{P(z)}\right] = 4.343\alpha_p\,(\text{km}^{-1}) \tag{3-1c}$$

This parameter is generally referred to as the *fiber loss* or the *fiber attenuation*. It depends on several variables, as is shown in the following sections, and it is a function of the wavelength, as is illustrated by the general attenuation curve in Fig. 3-1.

Example 3-1. An ideal fiber would have no loss so that $P_{out} = P_{in}$. This corresponds to a 0-dB/km attenuation, which, in practice, is impossible. An actual low-loss fiber may have a 3-dB/km average loss at 900 nm, for example. This means that the optical signal power would decrease by 50 percent over a 1-km length and would decrease by 75 percent (a 6-dB loss) over a 2-km length, since loss contributions expressed in decibels are additive.

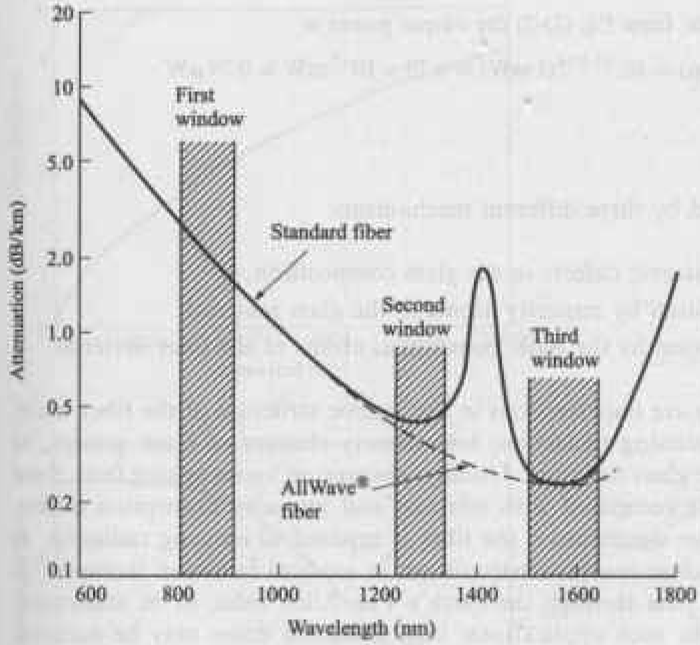

FIGURE 3-1
Optical fiber attenuation as a function of wavelength yields nominal values of 0.5 dB/km at 1300 nm and 0.3 dB/km at 1550 nm for standard single-mode fiber (solid curve). This fiber shows an attenuation peak around 1400 nm resulting from absorption by water molecules. The dashed curve is for a water-free AllWave® fiber (data courtesy of Lucent Technologies).

Note that App. D contains a review of decibels, which are used to facilitate calculations of power budgets in a light-wave link. As described therein, optical powers are commonly expressed in units of *dBm*, which is the decibel power level referred to 1 mW.

Example 3-2. Consider a 30-km long optical fiber that has an attenuation of 0.8 dB/km at 1300 nm. Suppose we want to find the optical output power P_{out} if 200 μW of optical power is launched into the fiber. We first use Eq. (D-2) to express the input power in dBm units:

$$P_{in}(\text{dBm}) = 10\log\left[\frac{P_{in}(\text{W})}{1\,\text{mW}}\right] = 10\log\left[\frac{200\times10^{-6}\,\text{W}}{1\times10^{-3}\,\text{W}}\right] = -7.0\,\text{dBm}$$

From Eq. (3-1*c*) we then have that the output power level (in dBm) at $z = 30$ km is

$$P_{out}(\text{dBm}) = 10\log\left[\frac{P_{out}(\text{W})}{1\,\text{mW}}\right] = 10\log\left[\frac{P_{in}(\text{W})}{1\,\text{mW}}\right] - \alpha z$$
$$= -7.0\,\text{dBm} - (0.8\,\text{dB/km})(30\,\text{km}) = -31.0\,\text{dBm}$$

In units of watts, from Eq. (D-2) the output power is

$$P(30\,\text{km}) = 10^{-31.0/10}(1\,\text{mW}) = 0.79 \times 10^{-3}\,\text{mW} = 0.79\,\mu\text{W}$$

3.1.2 Absorption

Absorption is caused by three different mechanisms:

1. Absorption by atomic defects in the glass composition.
2. Extrinsic absorption by impurity atoms in the glass material.
3. Intrinsic absorption by the basic constituent atoms of the fiber material.

Atomic defects are imperfections in the atomic structure of the fiber material. Examples are missing molecules, high-density clusters of atom groups, or oxygen defects in the glass structure. Usually, absorption losses arising from these defects are negligible compared with intrinsic and impurity absorption effects. However, they can be significant if the fiber is exposed to ionizing radiation, as might occur in a nuclear reactor environment, in medical radiation therapies, in space missions that pass through the earth's Van Allen belts, or in accelerator instrumentation.[6-9] In such applications, high radiation doses may be accumulated over several years.

Radiation damages a material by changing its internal structure. The damage effects depend on the energy of the ionizing particles or rays (e.g., electrons, neutrons, or gamma rays), the radiation flux (dose rate), and the fluence (particles per square centimeter). The total dose a material receives is expressed in units of rad(Si), which is a measure of radiation absorbed in bulk silicon. This unit is defined as

$$1\,\text{rad(Si)} = 100\,\text{erg/g} = 0.01\,\text{J/kg}$$

The basic response of a fiber to ionizing radiation is an increase in attenuation owing to the creation of atomic defects, or attenuation centers, that absorb optical energy. The higher the radiation level, the larger the attenuation, as Fig. 3-2*a* illustrates. However, the attenuation centers will relax or anneal out with time, as shown in Fig. 3-2*b*. Thus, the specific radiation-induced loss in fibers is complex, and some guidelines for application have been recommended.[7]

The dominant absorption factor in fibers prepared by the direct-melt method is the presence of impurities in the fiber material. Impurity absorption results predominantly from transition metal ions, such as iron, chromium, cobalt, and copper, and from OH (water) ions. The transition metal impurities which are present in the starting materials used for direct-melt fibers range between 1 and 10 parts per billion (ppb), causing losses from 1 to 10 dB/km. The impurity levels in vapor-phase deposition processes are usually one to two orders of magnitude lower. Impurity absorption losses occur either because of electronic transitions between the energy levels associated with the incompletely filled inner subshell of these ions or because of charge transitions from one ion to another. The absorp-